DYNAMIC STUDIES OF ROLLING ELEMENT BEARINGS WITH WAVINESS AS A DISTRIBUTED DEFECT

by

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Submitted
in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI
MARCH-2013

TO MY FATHER

Certificate

This is to certify that the thesis entitled "**Dynamic Studies of Rolling Element Bearings with Waviness as a Distributed Defect"** being submitted by **Mr. Chettu Kanna Babu** (2006ITZ8049) to the **Indian Institute of Technology Delhi**, New Delhi, India, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our guidance and the candidate has fulfilled the requirements for the submission of this thesis. The thesis, in our opinion has attained a standard required for a Ph.D. degree of this institute. As per our awareness the results contained in this thesis have not been submitted in part or in full to any other university or institute for award of any degree or diploma.

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Acknowledgements

I wish to express my deep sense of gratitude and indebtedness to my thesis supervisors, **Prof. N. Tandon** and **Dr. R. K. Pandey**, for their constant support, inspiration and encouragement during the course of this endeavor. Their comments and suggestions at various stages have immensely improved my understanding of the subject and paved the way from time to time for solutions of governing equations and experimental studies reported in this thesis.

I acknowledge all the supports provided by **Prof. O. P. Gandhi** (Head, Industrial Tribology, Machine Dynamics and Maintenance Engineering Centre) in completion of this thesis. I am highly thankful to **Dr. A. K. Darpe** (External expert in SRC), Department of Mechanical Engineering, Indian Institute of Technology Delhi, for his valuable suggestions and vital feedbacks during my presentations. I express my sincere gratitude to internal SRC members **Prof. O. P. Gandhi** and **Prof. V. K. Agarwal** for their kind technical suggestions and help time to time. I would also like to acknowledge the directly or indirectly help provided by other faculty members of IIT Delhi during perusal of this study.

Vital helps rendered by **Mr. Ashok Kumar, Mr. Avatar Singh** and **Mr. P. N. Jha** in Machine Dynamics Laboratory (ITMMEC) during my experimental studies are gratefully acknowledged. I would also like to thankfully record the necessary helps extended by other staff members of the centre. I must mention and record my special thanks to my co-researchers **Dr. Vinod Patel**, **Ms. Sidra Khanam** and **Mr. U. Sudeep** at

ITMMEC, for their moral and academic interaction supports during pursue of this endeavor.

I most respectfully record my gratitude to the management of **Hindustan Aeronautics Limited, Bangalore, India,** for granting needful permission and sponsoring me to pursue my Ph. D. programme at ITMMEC, IIT Delhi. My sincerely thank with great regards to **Dr. V. Sridhara**, **Mr. P. V. Mustafa**, **Prof. B. Satyanarayana**, **Mr. M. N. Manjunatha, Mr. R. K. Bharati, Mr. P.R. Nagasubramanian, Mr. G. Harikrishnan, Mr. Girish K Degonkar** and **Prof. K. Ramji** for their helping hands during pursuing of my research activities. I also thank **Mr. R. P. Singh**, **Mr. Asit Behra**, **Mr. Viswanath**, **Dr. Ramkumar** and **Dr. G. V. Rao** for their kind helps during pursuing of this research programme.

I express my deep felt love and gratitude to my family members, **wife** (Umamaheswari), **daughter** (Shanmukha priya), and all nears and dears for having patiently put up with me and constantly encouraging me throughout this endeavor at the cost of their own sufferings.

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Abstract

Rolling bearings find wide applications in industrial and domestic machines/appliances. In spite of high precision manufacturing of the components of the rolling bearings, geometrical imperfections happen to arise in the bearings at the beginning (in new piece itself) due to manufacturing/assembly constraints or during the use of the bearings. The geometrical imperfections invite vibrations in the bearings during operation, which highly influence the rolling bearing's performance parameters such as temperature rise, wear and reliable life. Therefore, it is worth exploring the combined effects of the geometrical imperfections and frictional moments on the vibration behaviors of the rolling bearings. In this thesis attempts have been made to understand the role of the geometrical imperfection (distributed defect) on the vibrations of rolling bearings using theoretical and experimental approaches. The main objective of the study reported in this thesis is to develop a general and realistic non-linear 6-DOF dynamic model of a rotor-bearings system for investigations of vibrations of the rotor-bearings system. The waviness on races and balls, frictional moments, shaft deflection, centrifugal force and gyroscopic moment of the balls has been accounted in this proposed analytical/numerical model for studies of the vibrations. However, the additional objective of this thesis is to investigate the combined influence of the lubricant starvation and waviness on the vibrations of the bearing-rotor system.

Non-linear vibration analysis of angular contact ball bearings has been simulated herein considering load dependent and load independent components of frictional

moments in the bearing. Six degrees of freedom of rigid rotor is considered in the dynamic modeling of the rotor-bearing system. Moreover, surface waviness on inner race, outer race and ball is considered and has been incorporated in the model by representing it as sinusoidal function. The proposed model is validated with the experiments and published results of researchers by incorporating needful changes in degrees of freedom in the proposed model. Based on the computed results, it is observed that the load independent component of frictional moment significantly reduces the amplitudes of vibrations. The influence of inner race waviness is relatively more on the vibration in comparison to waviness of outer race and ball. Moreover, at large amplitude of waviness and increase in the order of waviness, vibration enhances considerably.

Non-linear vibration model of the angular contact ball bearings supported rigid rotor has been simulated herein considering the combined influences of the lubricant starvation and waviness on the balls and races of the bearings. Based on the results of the proposed model, it is observed that for the same order of the waviness on the bearing components, the vibrations in the transverse direction of the rotational axis enhances considerably in case of starved contacts in comparison to fully flooded contacts of the bearings. Moreover, the influence of inner race waviness is relatively more on the vibrations in comparison to same orders and amplitudes of waviness present on outer race and balls. At large amplitudes of waviness and increase in the orders of waviness, vibrations enhance significantly. It is necessary to mention here that due to severity of lubricant's starvation; the amplitudes of vibrations reach the same order as due to increase in the orders of the waviness on the races and balls. Based on the proposed

vibration model, authors found that the effects of starvation on vibrations are significant and it must be accounted for in the dynamic models of bearings for achieving accurate results.

The model has also been used for vibration analysis of high speed angular contact ball bearings supporting the rotor bearing system under the effect of shaft deflection, centrifugal force and gyroscopic moment of the ball. Concepts pertaining to inner ring centrifugal displacement, frictional moments and waviness of balls and races have also been discussed. Three dimensional Timoshenko beam element with six degrees of freedom for each node has been adapted for computation of shaft deflection. Newton Raphson with centered finite divided difference formulae have been used to solve the deformation consistent equations. Nonlinear equations have been solved using the Runge-Kutta 4^{th} order method. Results have been validated through comparison with the research results established by predecessors. Based on the computed results, it is observed that the influence of outer race waviness on vibration is more as compared to the influence of inner race waviness and ball. Due to the centrifugal force and gyroscopic moment, side bands are observed around defect frequency and operating frequency in the spectrum. It is also important to note that the vibration enhances considerably owing to increase in the order and/or amplitude of waviness. Other major reasons attributing to change in vibration frequencies are seen as shaft deflection, centrifugal force and gyroscopic moment of the ball

Experimental investigations of vibration response of deep groove ball bearings in presence of waviness on either of bearings' races with fully flooded and starved condition

are attempted. Waviness on inner and outer races of bearings is created by electric discharge machining. Experimentations for vibration response of bearings with fully flooded and starved conditions have been conducted on a test rig using both healthy and defective (with waviness) bearings. The vibration signals have been acquired using accelerometer, signal conditioner and FFT. The acquired signals have been processed in time and frequency domains. Characteristic defect frequencies and its harmonics are broadly investigated in the frequency spectra. Comparisons of vibration responses of healthy and defective (with waviness on either of races) with fully flooded and starved bearings are provided and discussed the effect of starvation on vibrations.

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Contents